11. LINAC RF SYSTEMS

Availability of Klystrons

Presently available L-band klystrons used in other accelerators are listed in Table 11-1. The term “output power” refers usually to the *saturated* output power but is not consistently defined. This figure should be at least 15 - 20% higher than the nominal required power at the cavity input, to take into account losses in the circulator and feeder line, lack of linearity close to the saturation limit, end-of-life condition, etc.

Table 11-1 Available 1.3 GHz CW klystrons

Manufacturer	Designation	Frequency	Output power	Where used
CPI	VKL7811ST	1300 MHz	10 kW	Stanford, Rossendorf
NORTHROP GRUMMAN	L-4941	1497 MHz	8 kW	JLab

The CPI klystron operates at the desired frequency, it features the highest power output which covers the first project phase adequately. The NORTHROP-GRUMMAN klystron can be converted to the lower frequency, but this involves redevelopment and still results in a unit with smaller output power.

Other manufacturers have been contacted with mostly negative results. THALES delivers a pulsed 1300 MHz klystron of >40kW average power to CERN, but would not consider its conversion to CW unless a large quantity is involved. TOSHIBA may have suitable items, although their response is pending.

It follows that the VKL7811ST klystron from CPI is presently the best choice pending availability from other manufacturers.

Going to Higher Beam Power

The possibility of operating at higher beam power is explored in response to possible future needs of the user community. High beam power entails high generator power, and a 10-kW klystron will be at its limit for about 120 μA beam current. CPI will propose upgraded versions of the VKL7811ST unit for 20, 30 and 40 kW output power. These units are expected to feature electromagnetic instead of permanent-magnetic focusing, to work at higher HV voltage together with lower perveance to improve the efficiency, and may possibly be equipped with an improved output window.

However, increasing the rf power is not necessarily the best approach, since apart from higher investment and operating cost it also involves possible problems with the cavity input coupler, the beam dump, and the cryogenic system, to name but a few.

The rf power requirement may be reduced by several methods:

Fast tuning of the cavity. This aims at reducing the tuning error by means of e.g. a piezoelectric tuner inside the cavity, or a mechanical/ferrite tuner in the feeder line. This method is most effective at low beam currents but of limited effect at higher intensities (see Figure 9-7 of Chapter 9-Superconducting RF Linacs).

Linac energy management 'LERM'. Cavities with lower than the expected maximum tuning errors require considerably less rf power. At low beam currents, a perfectly tuned cavity needs only half the amplifier power compared to a unit with the maximum admissible tuning error. This follows from the fact that the tuning error limit for optimum coupling coincides with the 3-dB bandwidth point, and can also be seen in Figure 9-6 of Chapter 9-Superconducting rf Linacs. The strategy for a population of cavities with different microphonics errors is to attribute a larger fraction of the total required voltage to the well-tuned cavities while decreasing the fraction to off-tune units. An automated optimization algorithm is reported to have achieved a benefit of about 25% average amplifier power [1].

RF energy recovery. The high-energy beam is not dumped but decelerated by being returned through the linac with phase reversal to deliver its energy back to the system. Due to their long time constant, the SC cavities integrate over the accelerating and decelerating cycle such that the effective beam current is reduced by an order of magnitude or more. Besides the advantages of reducing the power in the coupler and in the cryogenic system, the dumping of the beam at low energy (10 MeV) is also very attractive from a radiation protection point of view. The drawback, however, is the necessity of a beam return line to recirculate the beam after the final arc, and the additional complexity of controlling the beam through four more passes.

A possible development scenario is therefore to start the project with low beam charge and low repetition rate (1nC and 10 kHz respectively) which can be safely handled by the available 10-kW klystrons. Operation at higher beam intensity is possible by voltage distribution shaping, the introduction of fast tuners, and eventually by rf power recovery. This should allow the beam current to be increased gradually to an ultimate design goal of 1200 μA, without the need of higher-power klystrons. This does not mean however that the possibility of using improved klystrons from the beginning should be discarded.

RF System Layout

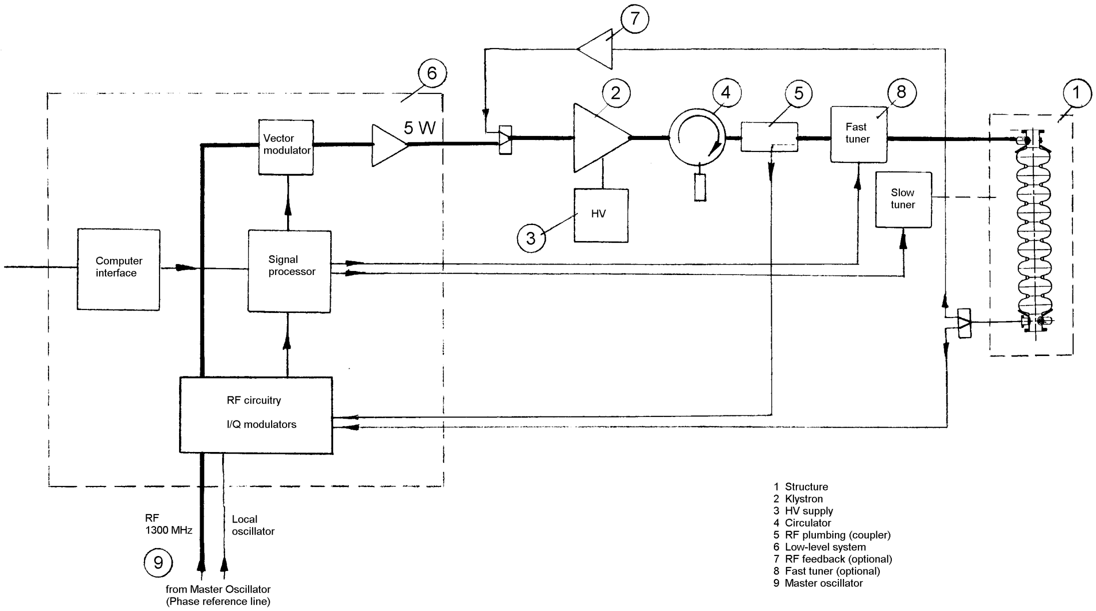

Figure 11-1 Linac rf system schematic layout

The design of the rf system follows well established principles, and the schematic layout is shown in Figure 11-1. The only element of predetermined limited lifetime is the klystron, for which no semiconductor equivalent (yet) exists. All elements are of course subject to "unscheduled maintenance" but are well within standard technology.

Comments to the different parts of the system:

1. <u>Accelerating structure</u>. A cryostat contains eight or more 9-cell TESLA cavities, together with accessory equipment such as steering magnets. As the design of cavities and cryostat is constantly improved in the context of other large projects, the final configuration will depend on the state of the art at project time.
2. <u>Klystron.</u> (see above).
3. <u>HV supply</u>. There is a choice of two technologies, namely switching supplies (cheap, efficient, low stored energy and flexible, but prone to high ripple) vs. continuously regulated supplies (opposite characteristics). The steady progress in semiconductor and ferrite technology had a major impact on the structure of switching power supplies which become lighter and smaller due to ever-increasing switch frequencies. The voltage of the presently available klystrons (16 kV) is relatively low which alleviates insulation and maintenance problems.
4. <u>Circulator</u>. This ferrite-loaded non-reciprocal device protects the klystron by diverting the reflected wave from the highly mismatched cavity input port to a separate power absorber.
5. <u>RF plumbing</u>. The entire high-power rf distribution is composed of WR650 waveguide components, except where building constraints may dictate short sections of coaxial lines.

The size of the waveguides is determined by the operating frequency. Due to the large dimensions their breakdown limit is much higher than the operational fields, therefore no special precautions such as pressurization are necessary.

6. Low-level system. Consisting of two parts:

   Analog rf circuitry. Standard analog building blocks such as power splitters, mixers and filters are used to manipulate and distribute the operational frequency, based on the signals received from the master oscillator. A vector modulator for the control of amplitude and phase, and a 5-W semiconductor amplifier are the most prominent parts in the main signal path that leads to the input of the klystron. Other analog modules perform the signal conditioning to transform the signals received at 1300 MHz to a frequency around 80 MHz for treatment by the digital controller.

   Digital signal processor. This is the part where the progress in signal handling and information processing leads to spectacular results in terms of system diagnostic possibilities and operational flexibility. The conditioned signals at the frequency of ~ 80 MHz are converted into digital form by A/D converters, treated by the digital signal processor, passed through D/A converters and finally routed to the outputs. These include in particular the vector modulator for control of the cavity field, together with actuators such as the cavity tuner.

   An accelerator rf system comprises at least three interacting feedback loops, namely for cavity amplitude, cavity phase and resonator tuning. All of these feedback loops are implemented here in a fully digital form to allow the easy introduction of different control algorithms by software. While the control of each cavity is self-contained and local, a fast interface allows remote operation and data collection by a central computer. A separate section of the digital controller takes on the mundane tasks of an interlock system such as switching the system ON/OFF and to protect the equipment in case of failure.

7. RF feedback (optional). *Direct* or *fast* rf feedback is part of many modern rf systems. It permits an increase in the small-signal rf bandwidth and linearizes the transfer function of the klystron. Its implementation for a 9-cell cavity is more complicated than for a single cell due to the adjacent secondary resonances but proven solutions exist to solve this problem [2]. It is an optional device that can be added at a later stage.

8. Fast tuner (optional). The aim of a fast tuner is to reduce the rf power requirements by decreasing the cavity tuning deviations. It can be implemented as a mechanical or as an electronically controlled ferrite-based device, and is most effective at low beam currents as explained above.

9. Master oscillator and phase reference line. All linac rf chains receive an input signal from a phase reference line to assure phase coherence in the different resonators. The reference signal is created in a common master oscillator and distributed by a temperature-compensated line that runs along the linac structures. Directional couplers in the pickup points together with a low-reflection generator assure a high degree of mutual decoupling. It is planned to derive the master oscillator from the optical laser resonator to meet the stringent synchronization requirements.

Power Consumption

The necessary peak AC power to generate the maximum rf power of 10 kW is determined by the efficiencies of the klystron (~33%) and the HV power supply (~90%); it amounts to about 33.7 kW. It is expected that the average power consumption for low beam current is about 25% lower. Power requirements for ancillary devices such as filaments, blowers, ion pump on the klystron etc. are estimated at 500 watts leading to a total of about 34.2 kW peak, 27.5 kW average. The total requirement for the 32 rf chains of the main linac is therefore 1.1 MW peak, 0.88 MW average.

Conclusions

We find that a net klystron power of 8kW per cavity is required to accelerate 1nC bunches in four passes at a repetition rate of 10 kHz. Substantially larger beam currents can still be handled with the same klystrons but will ultimately require rf power recovery by a return line. The main linac rf parameters are summarized in Table 11-2.

Table 11-2 Main linac parameters

Energy gain per pass in main linac	600 MeV
Accelerating gradient in main linac	20 MVm^{-1}
Design voltage per cavity	20 MV
Duty factor	CW
Wall power losses per cavity	42 W
rf losses per cryomodule	336 W
Average beam current (4 passes)	40 μA
Beam power per cavity	800 W
Cavity Q_0 (unloaded)	$1 * 10^{10}$
Cavity R/Q ("linac" definition, $P=V^2/R$)	1036 Ω
Cavity coupling factor β	384
Cavity Q_L (loaded)	$26x10^6$
Cavity loaded bandwidth	50 Hz
Total main linac rf power	320 kW peak, 256 kW average
Total main linac AC power ($\eta_{overall}$= 29.7%)	1.1 MW peak, 0.9 MW average

REFERENCES

[1] J. R. Delayen, L. R. Doolittle, C. E. Reece, "Operational optimization of large-scale srf accelerators," Proc. 1999 Particle Accelerator Conference, New York, 1999

[2] D. Boussard, H.P. Kindermann, V. Rossi, "RF Feedback applied to a Multicell Superconducting Cavity," Proc. EPAC 88, June 1988, Rome, Italy.